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The Development of a Robust Crack Growth Model for Rotorcraft Metallic Structures.

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1 INTRODUCTION

In the United Kingdom, helicopters have traditionally been designed using safe life principles. However, proposed changes to the airworthiness regulations require that, in the future, structures are qualified using flaw growth methods. Therefore, a robust crack growth model is required. A collaborative project has been undertaken by GKN Westland Helicopters, DERA, Cranfield University and nCode International to develop such a model and define the methodologies required for its implementation. The work was funded by the Department of Trade and Industry and the Ministry of Defence whose support is gratefully acknowledged. This report describes work carried out in the collaborative project and the recommendations formulated.

The project consisted of six main areas of investigation namely the derivation of stress intensity factors, determination of typical flight load sequences, measurement of fracture mechanics material properties for use in models, measurement of crack growth data for model verification, evaluation and development of crack growth models, and definition of a helicopter damage tolerance methodology. The project considered two areas of helicopter design, these were 1) a dynamic rotating component found in a rotorhead and 2) a typical structural feature in the main load path lift frames. The two areas are fundamentally different and involve different materials and loading actions which may, therefore, require different damage tolerance approaches.

In this paper each of the six areas of investigation are described, with the main focus on the development and evaluation of crack growth models. The approach used for model development and evaluation was to increase gradually the complexity of the loaded structure. Initially, simple compact tension coupons subjected to constant amplitude loading were studied and models were evaluated against test measurements. The complexity of the loading was increased to include discrete loading events, compressive loading events, and finally two representative flight load sequences, Asterix and Rotorix, which were developed during the project. The complexity of the components was also increased, to include part through thickness cracks and finally structural elements representative of features in a rotorhead mast and an area of a main lift frame. At each of these stages, the models were evaluated against experimental measurements. From the results of the investigation, an overall methodology was developed for damage tolerance assessments, although a number of areas require further investigation. The applications and limitations of the approach are presented and recommendations for further work made.

2 OVERVIEW OF THE COLLABORATIVE PROGRAMME

Fracture mechanics based crack growth prediction programs require information on material properties, a description of constant amplitude crack growth rates in terms of Stress Intensity Factor range (SIF), and a description of SIF in terms of crack length. The first two sets of information were determined from experimental measurements made in this programme. Tensile properties and fracture toughness measurements were made on each of the two materials investigated; a Titanium and an Aluminium-Lithium forged alloy. Crack growth data were measured using compact tension (CT) specimens subjected to constant amplitude loading at four tensile stress ratios, R=0.1, R=0.4, R=0.7 and R=0.9. Crack growth rate data at negative stress ratios (R=-0.5 and R=-1.5) were generated using Single-Edge-Notched-Tensile (SENT) specimens. In addition crack growth rate data were generated in the near threshold SIF region at each of the tensile stress ratios.

In order to validate the models, further experimental crack growth rate data were required for comparison with predictions. The approach adopted was to increase the complexity of the test pieces and the loading independently to allow models to be calibrated prior to prediction of crack growth in representative structures subjected to helicopter loading spectra. The specimens selected were surface-crack-tension (SCT), to examine the growth of a part through thickness flaw, and two structural elements, one representing a feature in a rotorhead mast and one representing a feature in a lift frame. The first loading sequences selected were simple variable amplitude loading (SVAL) which consisted of constant amplitude loading interspersed with large tensile load excursions (overloads) and small tensile load excursions (underloads). The second loading series consisted of the two sequences derived from strain gauge measurements, as described below.

The two helicopter structural locations studied in this project (rotorhead and lift frame) experience dynamic flight loading primarily due to the action of the main and auxiliary rotors. The loading spectra are complex and no standard sequences exist to simulate these regions. The standard sequences Helix and Felix [1,2] represent loading on rotor blades, and the mix of helicopter missions and manoeuvres described by their load generation program, HIXFIX, was thought to be appropriate to the loading experienced by the two structural locations of interest in this project. Accordingly, HIXFIX was used in the project in combination with strain gauge data measured on a Westland/Agusta EH101 and a Westland Lynx helicopter in order to define two new sequences named Asterix[3]and Rotorix[4], relevant to a lift frame location and a rotorhead location respectively.

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In order to conduct a crack propagation analysis, Stress Intensity information is required as a function of applied load, crack length, and geometry. For many simple components, these data exist and can easily be incorporated into the crack growth models. SIF solutions for the CT specimen were obtained from ASTM E647, and participants were free to select solutions for the SENT and SCT specimens. SENT SIF solutions were already coded into most of the crack growth models, though in fact all were different. Solutions for the SCT specimen need to account for growth in the surface and thickness directions and again partners were free to select their preferred solutions; this is discussed further in section 3.3. No standard solutions were available for the two structural elements so alternative methods were investigated. These included Finite Element (FE) and Boundary Element (BE) methods and compliance functions derived from tests. The test derivation involved measuring crack growth rates and determining SIF's at equivalent growth rates from data obtained on CT specimens. 2-D and 3-D FE approaches were tried and good agreement was found indicating that the simpler 2-D approach was adequate. Overall it was decided that the experimental compliance function was best suited to the prediction exercise, though clearly this would not be a generally acceptable solution for the wide range of helicopter components which would need to be assessed in a damage tolerant design.

3 ASSESSMENT OF CRACK GROWTH MODELS

3.1 Assessment procedures

Crack growth prediction programs usually calculate the incremental crack extension for individual applied load cycles and sum them over the entire load sequence until some critical value is reached and the component fails. This requires the calculation of effective stress intensity factors at incremental crack lengths from which crack growth rates can be inferred using a database of constant amplitude data. The calculation of effective stress intensity factor requires the use of a model which accounts for load interaction effects. These load interactions may increase (accelerate) or decrease (retard) the rate of crack growth, depending on the relative magnitudes and frequencies of the applied loading cycles. Models which describe these load interactions are generally considered to be the most important aspect of crack growth prediction programs. A range of load interaction models were evaluated in the project, but various other procedures within the crack growth prediction programs were also examined. These other procedures are frequently overlooked and may in fact cause greater differences in predictions than those resulting from the choice of load interaction model. The procedures considered are presented and discussed in section 3.2.

Load interaction models vary not only in their complexity but also in the underlying mechanisms which they aim to describe. The simplest models recognise the role that the plastic zone plays in retarding crack growth when a load cycle is preceded by one of a larger magnitude. Such models are termed plastic zone interaction models and calculate load interaction effects based on the dimensions of the plastic zones due to the current and preceding load excursions. Plastic zone interaction models examined in the project include those developed by Wheeler[5] and Willenborg[6]. There have been many proposed improvements to the Willenborg model and a number of these have also been examined. A more sophisticated version of Willenborg has been adopted by nCode International in their Kraken program [7], which also considers crack closure in its calculations. Crack closure is the notional position during a load cycle at which the crack faces come into contact. In practice, crack faces do not close uniformly along their length at a specific load, but an 'average' load at which crack closure occurs within a cycle is a useful concept in determining the effective stress intensity range experienced by a growing crack. The effective stress intensity factor range can be simply determined from the maximum applied stress during the cycle to the minimum or closure stress, whichever is the greater. This concept is also used in the Loseq model developed by Fuhring [8] which like Kraken also uses plastic zone correction methods. A further group of models are based on strip-yield considerations which follow the Dugdale and Barenbladt approach. The region ahead of a crack tip is considered to be a thin strip of material which comprises rigid-perfectly plastic elements within the yielded zone. As the crack develops these rigid elements are maintained and those behind the crack tip now describe the behaviour in the crack wake. The stress distribution ahead of the crack tip, and in its wake are used to derive the crack closure load for any loading sequence. Models utilising this approach have been developed by Newman[9] and by de Koning and ten Hoeve[10] which are entitled Fastran and Stripy respectively. All of the models described above were evaluated in the project.

The models were assessed against experimentally determined fatigue crack growth data which were selected from a database generated as part of the project. The models were first used to predict crack growth rates in constant load amplitude tests as described in section 3.3. These data were then used to optimise the models and blind predictions were made of crack growth rates in tests where discrete loading events (overloads and underloads) were introduced. The ability of the models to predict changes in crack growth rates associated with these periodic load excursions is assessed in section 3.4. The experimental data were then used to further optimise the models prior to blind prediction of the complex variable amplitude loading (CVAL) tests. The prediction of CVAL crack growth rates is described in section 3.5.

The accuracy of the different crack growth models was assessed at each stage of the project. Some models were found to be inappropriate for specific applications and were dropped at various stages of the project. The most important modelling parameters were also defined by examining their effect on the accuracy of crack growth predictions. A summary of these findings and recommendations on the most appropriate procedures to be used for crack growth modelling of rotorcraft structures is presented in section 4.

3.2 Data fitting procedures

3.2.1 Crack growth data fitting methods

Fitting appropriate curves through experimental data may appear a trivial step in the crack growth prediction process, however, its importance needs to be assessed. Participants were free to choose a data fitting method and those selected included visual best-fits and fits obtained from commercial software packages. Fits were made for each of the four stress ratios in each of the two materials used in the experimental programme. Fits in the linear (Paris) regime were similar for all three methods. However, interpretation of the raw data in the threshold and near failure regimes, where data were

sparse, showed some variation between the methods (see fig 1). Fits to the Aluminium-Lithium data were less consistent, due to the higher scatter, than for the Titanium data. Variations in the near threshold region, will have a significant impact on predicted fatigue lives under spectrum loading. This is because cracks spend a significant proportion of their lives at short crack lengths and because a significant percentage of loads in a helicopter loading sequence are of small magnitude. These two effects result in a large percentage of the life of a cracked helicopter structure being spent in the near threshold crack growth regime.

The fits achieved by the different participants were used as input data to the LOSEQ model with all other parameters remaining constant. Thus variations in predicted growth rates could only result from the different data fits used. The differences in predicted lives between the most and least damaging data fits for Titanium range from 7% to 30% of the least damaging life with an average of 19%. The differences in predicted lives between the most and least damaging data fits for Aluminium-Lithium range from 11% to 41% of the least damaging life with an average of 25%. It can be concluded that average errors of 20% to 25% of the predicted life under constant amplitude loading can arise simply from the choice of method adopted for determining the best fit to the raw data.

3.2.2 Crack growth data representation

Having obtained curves which describe the crack growth data sets to be used, it is necessary to describe them in a form which can be interpreted by the various computer models. The simplest form of this is digitisation of the crack growth curves at selected points (within the limits of the program). Other data input methods used by the partners included fitting Paris, Walker or Forman equations to the crack growth data. In order to assess the importance of the data input method, a series of predictions were made at each of the four stress ratios for the Titanium material with the inputs listed above; all other parameters were kept constant.

The results show major differences between the predictions for the various data representation methods. Differences in predicted lives between the most and least damaging data fits range from 25% to 86% of the least damaging life with an average of 61%. This means that differences in predictions by a factor of 2:1 are typical and up to 4:1 are possible as a result of the data representation method. The most appropriate method was a tabular input of crack growth rates to be used in conjunction with an interpolation and extrapolation routine. The least successful method was, not surprisingly, a single Paris representation, whilst the Forman equation, and to a lesser extent the Walker equation, over-predicted the effect of stress ratio on crack growth, resulting in consistently conservative predictions at high stress ratios. For the low stress ratios predictions were conservative at low delta K and unconservative at high delta K.

3.3 Constant amplitude loading (CAL)

The constant amplitude part of the programme was undertaken to validate the models for a range of specimen and crack geometries, and loading actions. The test programme focused on CT specimens, but included SENT and SCT specimens to examine compressive loading excursions and part-through-thickness cracks respectively. There were two parts to the prediction exercise for constant amplitude loading, the first involved a blind prediction and the second allowed model optimisation to minimise differences between predicted and experimental measurements. The final part of the constant amplitude programme was to perform predictions, using the optimised models, of crack growth in two structural elements, one representative of a feature in a rotorhead mast and the second of a feature in a main load frame.

Model calibration resulted in significant improvements in predictions; errors in predicted lives were within +/- 40% of the test life, and 60% were within +/- 10% of the test life for the Titanium CT tests (see for example fig 2). However, due to the higher scatter in the Aluminium Lithium data, errors were more than double those found for Titanium. The largest errors occurred at the low stress ratios (0.1 and 0.4), but predictions at the higher stress ratios (0.7 and 0.9) were generally quite good.

Cracks in the CT specimens were fairly uniform through the thickness of the material. In general, however, cracks are quarter or semi-elliptical in shape for a large percentage of the life of a component, particularly in materials of the thickness considered in this programme. SCT specimens were selected for use in this programme as cracks in this type of specimen remain semi-elliptical in shape for the majority of the fatigue life. Most of the models do not have the capability of predicting crack growth in both surface and through thickness directions, so some simplifications and modifications were required to the computer codes. Each participant was free to choose how crack growth would be represented but data predictions were required of crack growth on the specimen surface as a function of crack length. Various crack growth options were selected which included; constant aspect ratio, variable aspect ratio calculated from Newman and Raju[11], and compliance solutions from test measurements.

Methods which assume a constant crack aspect ratio equal to that of the initial flaw were conservative, as the cracked area was always greater in the predictions than in the test. The Newman and Raju approach gave reasonably accurate predictions, but as expected best accuracy was obtained by using the test compliance curve. Since this will not, in general, be available independent calculation of growth rates in the two directions using approximate methods such as Newman and Raju are recommended in preference to constant aspect ratio assumptions.

Analyses of measured loads at the selected structural locations showed that some minor compressive load excursions were present. A SENT specimen was selected to examine the effect of compressive loading excursions on crack growth and to facilitate evaluation of the prediction models with a compressive component of loading present. Crack growth tests were conducted on SENT specimens at stress ratios of R=-0.5 and R=-1.5. Significant discrepancies between predictions (using tensile stress ratio data only) and experimental measurements were found at R=-1.5, which were generally non-conservative (see for example fig 3). At a stress ratio of R=-0.5, predictions were still non-conservative but the results were much closer to the measured behaviour. It was concluded that predictions of crack growth under partial compressive loading could not be predicted accurately using any of the models if tensile constant amplitude crack growth data only were available. The predictions became less accurate, and more non-conservative, as the compressive

loading content was increased. For predictions in which compressive loading is to be applied, it is important to ensure that crack growth rate data for compressive constant amplitude loading are used as model inputs which cover the complete range of stress ratios for which predictions are required.

Predictions of growth rate in the two structural elements using a compliance function derived from experimental measurements and analysis predicted trends in the crack growth curves extremely well and the total lives were within 30% of the measured values.

3.4 Simple variable amplitude loading (SVAL)

Fatigue crack propagation tests were performed on CT and SCT specimens which were identical to those used in the constant amplitude part of the programme. Fatigue tests on CT specimens consisted of constant amplitude loading at stress ratios of 0.1, 0.4 or 0.7, with different load events applied at crack lengths of 16, 20 or 24mm. The events superimposed on the constant amplitude loading sequence consisted of single overloads (OL), double overloads (DOL) or a single overload followed by an underload (OL/UL). The magnitude of the overload ratios (peak load/peak constant amplitude load) were typically 1.47, 1.75 and 2 at crack lengths of 16, 20 and 24mm respectively. The underload ratio (minimum load/peak constant amplitude load) was 0.1. The double overloads were not applied on consecutive cycles but separated by 3000 load cycles such that the second overload was applied at a point where crack retardation was active as a result of the first overload. The underload in the OL/UL tests were applied immediately following the overload. Fatigue tests on SCT specimens were similar to those described above. Single overloads, double overloads and overloads followed by underloads were applied at crack lengths of 5, 7 or 9 mm. Overload ratios varied from 1.25 to 2 and were superimposed on constant amplitude loading with stress ratios of 0.1, 0.4 or 0.7.

In order to compare the accuracy with which the models predicted these events, two metrics were defined; a) the number of loading cycles, and b) the crack extension over which crack acceleration and retardation occurred. These parameters are relatively simple to determine from predictions, by setting appropriate flags in the computer programs. Determination from experimental data is rather subjective so a fixed procedure was defined to ensure a uniform approach. Detailed predictions were made of crack growth at cyclic intervals prior to and immediately following individual load events.

The Wheeler model predicted delay cycles typically between a factor of two too small or too large, though the average for all tests was close to unity. The predicted delay distance was always considerably smaller than observed in test, the average prediction being about 10% of that observed. The predictions using Loseq were generally better than those using the Wheeler model. The delay cycles were between 0.48 and 1.36 of those observed in test. The delay crack lengths were slightly better than for the Wheeler case but were still typically only 16% of those observed in tests. Crack arrest was predicted for all cases where arrest was observed in tests but also for three cases where arrest did not occur in tests. The Stripy model predicted delay cycles closest to those observed in test for a stress ratio of R=0.1, but predicted delay cycles for all other cases were less than 0.65 of those observed in tests and always less accurate than for both the Loseq and Wheeler models. In contrast, the delay crack lengths predicted by Stripy were more accurate than those predicted by Loseq or Wheeler.

Kraken was used by two participants, one showed a bigger variation in predicted delay cycles than any of the other models, ranging from 0.024 to 4.66; the results obtained by the other participant showed much less variation. Similarly, the delay lengths predicted by the first participant showed a much wider variation than predicted by the second participant. For Kraken the delay cycles and delay lengths were closely correlated, which indicates that the crack growth rates are being more accurately predicted than by the other models.

Having examined the errors between predicted and experimental delay lengths and cycles and also any differences in growth rate characteristics, the participants were faced with the task of optimising their models once again. The discrepancies in delay cycles were mainly related to crack growth in the near threshold region. Accordingly most of the effort to optimise the models was spent in adjusting the constant amplitude crack growth rate data in this regime. All CT-SVAL predictions were repeated using the optimised models, and significant improvements were found as can be seen for example in figure 4 which shows blind and optimised predictions for a range of models.

Having optimised the models to best represent the measured SVAL data on compact tension specimens, the 'optimised models' were used to predict crack growth rates in SCT specimens under SVAL loading conditions. Predictions of tests conducted on Titanium specimens were generally quite good, although, out of the 52 predictions made, 17 still predicted arrest when none occurred in the test. Predictions of tests conducted on specimens of Aluminium-Lithium material were better than those for the Titanium material and crack arrest was not predicted for any of the tests.

3.5 Complex variable amplitude loading (CVAL)

The aim of this phase of the programme was to determine whether accurate predictions could be made of crack growth in structural components, using the procedures developed in the programme. Predictions were made of crack growth in CT and SCT specimens, and structural elements subjected to the two sequences Asterix and Rotorix. Predictions of tests on CT specimens subjected to Asterix loading were rather disappointing in that predictions were in error by up to a factor of ten, and the greatest errors occurred for predictions which were non-conservative. The Willenborg model predicted lives within a factor of about 3 but was overall non-conservative. The generalised version of Willenborg predicted longer lives than the original version and as a result they were consistently non-conservative by a factor of up to 10. Wheeler predictions were very poor and were also consistently non-conservative by a factor up to 10. The Loseq model predictions were non-conservative and resulted in errors of up to a factor of 5. Kraken predictions were within a factor of two of the test life, and were consistently conservative. Esacrack, which is a linear summation model taking no account of load interactions, generally predicted results in close agreement with the experimental results.

Linear summations were made for each of the models to examine a) the magnitude of the predicted load interactions

and b) whether linear summations would yield consistently conservative predictions. Relatively small load interaction effects (see fig 5) were predicted by the two Willenborg models (less than 20% increase in life), very large load interaction effects are predicted by Wheeler (factor of ~4 increase in life) and moderate load interaction effects are predicted by Loseq (factor of ~2 increase in life). More importantly, all of the predictions were non-conservative.

Predictions of tests on CT specimens subjected to Rotorix loading were similar to those observed for Asterix loading. Kraken predicted consistently conservative lives, generally within a factor of two, whilst all of the other models gave unconservative predictions. Linear summations were again non-conservative for the Wheeler, Willenborg, Generalised Willenborg and Loseq models.

The fits used for the Loseq, Willenborg, modified Willenborg and Wheeler models were all selected to best fit the crack growth data supplied and also to best fit the CAL and SVAL test results. For these models, crack growth rate data are described independently for each of the stress ratios tested. In contrast, a best fit to all of the constant amplitude data is selected automatically within the Kraken program. The data fits for each model were found to be quite similar for R=0.1 and R=0.4, but these will have little effect on the CVAL predictions, since most of the load cycles in Rotorix are at much higher stress ratios, typically between 0.7 and 0.9. The fits used in the different models at these higher stress ratios were quite different (see fig 6). Notably, the fits used by Kraken give crack growth rates significantly greater than those of the other models for a given stress intensity factor over the entire stress intensity factor range at R=0.9 and at stress intensity factor ranges less than 10 MPa. $\sqrt{m}$ at R=0.7. The predicted crack growth rates and endurances under Rotorix loading will be dominated by growth rates in the low stress intensity factor region and consequently Kraken predictions will be much shorter than those of the other models if a linear summation routine is used.

To study the sensitivity of predicted growth rates to the selected data fits, predictions were performed using the linear Loseq model. The resultant predictions for a compact tension specimen using the Rotorix loading sequence with a maximum load of 10 kN are presented in figure 7. The effects of the assumed data fits are clearly demonstrated with Kraken predicting the shortest lives, as expected. A similar exercise was undertaken for the Aluminium-Lithium material using Asterix loading and similar results were found . Predictions of SCT crack growth rates for Asterix and Rotorix loading gave similar results to those for compact tension specimens i.e. predictions using Kraken were conservative and all other predictions were non-conservative.

Predicted crack growth in the Titanium structural element was completely different to that observed in CT and SCT specimens. All predictions with the exception of Wheeler and Loseq were conservative and in extremely good agreement with test results. Kraken predictions were consistent with those made for tests on CT and SCT specimens in that they were conservative and within about 20% of the measured test endurances. The differences in crack growth patterns from those observed in CT and SCT predictions are that the Loseq, Wheeler and Willenborg predictions were conservative for the structural element tests. Predictions for structural element tests in Aluminium-Lithium material, however, were similar to those reported for the CT and SCT tests under CVAL loading in that Kraken produced conservative results and all of the other models were non-conservative.

4 DISCUSSION

Factors which can affect the accuracy of crack growth predictions have been investigated and their importance assessed. The method chosen to fit a curve through the available raw data had a significant effect on the predicted crack growth; typically differences of 20 to 25% were found in the predicted lives. Of greater significance were the differences in predictions resulting from the method selected to represent the fitted raw data in the prediction programs. The differences between the four selected methods were typically 2:1 with peak values of around 5:1. A simple Paris equation was found to be unsuitable and the Forman and Walker equations were very conservative at the high stress ratios. It can be concluded that more complex equations (e.g. Newman) are required to represent the data. Alternatively a tabular input of fits to the raw data should be used in conjunction with an interpolation routine. The SENT prediction exercise demonstrated that constant amplitude crack growth rate data to be used in the models must cover the entire range of stress ratios that occur in the loading sequence for which predictions are required. Extrapolation of the data to stress ratios less than those included in the available data lead to significant errors in predictions.

The SCT prediction exercise examined various methods to describe stress intensity factors for part through thickness cracks. Various methods were used in the models and the simplest ones which assumed constant crack aspect ratio were found to be very conservative. The most appropriate method of those examined was the one in which crack growth along the surface and thickness directions was described using the Newman and Raju expressions. The structural element prediction exercise demonstrated that experimental determination of compliance is a good method for crack growth predictions. However, it should be noted that this is not a very practical solution for the number of complex geometries which will be encountered in helicopter structures and a robust analytical approach should be sought.

Evaluation of models against SVAL data was achieved by comparison of the crack extension (delay distance) and the cyclic interval (delay cycles) over which crack retardation occurred. Whilst the delay cycles were generally predicted to within a factor of 2 by all models, the delay distance was poorly represented and in 31 of the 35 predictions it was underestimated. The average delay distance ratios (predicted/measured) were very different in the models; 0.1 for Wheeler, 0.15 for Loseq, 0.37 for Stripy and 0.47 for Kraken. This gives an initial ranking of the models in their ability to predict the distance over which crack lengths will be affected by overload events. The predicted delay distance is closely related to the plastic zone size and the differences in predicted values were found to result primarily from the different expressions used in the models to calculate the plastic zone size.

However, it was significant that the delay distances following an overload were much greater than the plane strain overload plastic zone size (OLPZ). Typically the ratio of test delay distance to OLPZ size ranged form 3 to 22. This has been observed previously by Suresh[12] who invoked a crack closure argument to explain the prolonged delay distance. However, this does not offer a satisfactory mechanism

because the fractography results did not give any evidence of fracture surface damage consistent with roughness induced closure either before or after the overloads. The fracture surface appearance remained virtually unchanged so that it is unlikely that this mechanism gave prolonged delay distances.

Delay distances longer than the overload plastic zone size have also been observed by Shuter and Geary[13] who found that delay distances were shorter in plane strain specimens than in plane stress specimens. This observation provides a plausible explanation which is that different growth rates occur between the surface and interior of the specimen. Turner *et. al.*[14] suggest that delay responses are different through the thickness because of a variation in constraint from the plane stress surface to the plane strain interior. They found that the post-overload crack front had greater curvature than pre-overload due to crack 'tunnelling' in the plane strain interior.

The observations of Turner *et. al.* suggest that the surface plastic zone has a significant retarding effect on crack growth on the surface only, due to greater plasticity at the crack tip. This was not specifically observed in the tests, because the specimens were not broken open after each overload (they were used for subsequent overload tests). The DCPD method used in this investigation measures changes in cross-sectional area of the specimen so the crack length would be an average of the through-thickness crack front length. If retardation is minimal in the specimen interior and grows a significant distance before the surface region grows through the plane stress OLPZ then the DCPD system would measure a change in length greater than the OLPZ.

Delay cycles are more important than delay length in the prediction of crack growth life, and the success of efforts to improve predictions were measured using this parameter. The calibration exercise proved extremely successful and predictions of the SVAL data were improved significantly for all of the models. In particular it was possible to eliminate prediction of crack arrest following overloads in all cases where crack arrest was not observed in tests; this was not the case for blind prediction of the SVAL data. It can be concluded that calibration is an important part of the process in developing methods for crack growth prediction.

The accuracy of predictions under CVAL loading was rather disappointing. Predictions varied from a factor of two on the conservative side to a factor of five on the non-conservative side. The Kraken model predicted consistently conservative growth rates, whilst the other models (Loseq, Wheeler, Willenborg and generalised Willenborg) predicted non-conservative growth rates. The non-conservative predictions did not result from inaccurate modelling of load interaction effects as linear summations were also found to be non-conservative. Examination of the constant amplitude crack growth data used in the different models revealed that the Kraken description of crack growth rates at high stress ratios (R=0.7 and R=0.9) was considerably more damaging than the baseline constant amplitude data, whilst descriptions of constant amplitude crack growth data used by the other models were in good agreement with experimental data (see figure 8).

The sensitivity of predictions to the input data was further examined using the various constant amplitude data fits from the different models and performing linear summations with the Loseq model, thus eliminating any differences between the operation of the different models. This resulted in very similar observations to those described above for CVAL loading with Kraken data fits giving the shortest lives compared with those using data fits from the other models. The large differences in predicted fatigue crack growth and fatigue endurances can thus be attributed to the different constant amplitude crack growth rate data fits used in the models.

The sensitivity of data fits in the near threshold regime requires accurate data fitting. Experimental data will, in general, exhibit large scatter in this region which will preclude accurate data fitting. Further work needs to be carried out to define suitable data fitting methods. There is also growing evidence that crack growth in the threshold region is dependent on crack length. This has been accepted for the growth of short cracks for a number of years [15], and an investigation at a range of crack lengths is warranted. This may be an important addition to the models where short crack growth is not modelled explicitly.

It was also noted that the Kraken, Willenborg and generalised Willenborg predicted very little effect of load interaction, whereas the Loseq and Wheeler predicted a significant effect. This needs further study to establish the real load interaction effects and which models give the best representation. It is possible that the development of new models may be necessary to improve crack growth predictions for helicopter structures which describe the effects of underloads more accurately.

A further possible reason for the poor predictions of crack growth rates under the Asterix sequences is that the fracture surface morphology is very different to that observed in constant amplitude tests. The fracture surfaces of compact tension test pieces subjected to Asterix loading were quite smooth, as were those subjected to constant amplitude loading at low ΔK values. At high ΔK values, however, constant amplitude tests had rough surfaces resulting from transgranular cracking. The crack closure levels in the CA tests would, therefore, be higher due to this surface roughness. The predictions used the CA data to predict crack growth under Asterix loading, where the closure levels were lower. Thus the stress range experienced by the crack tip for any given crack length and stress ratio would be greater in the Asterix test than in the CA test. This is likely to result in non-conservative predictions as the assumed stress range experienced by the crack tip would be lower in the predictions (based on CA data) than in the Asterix tests. This also requires further investigation.

5 CONCLUSIONS

5.1 Predicted fatigue endurances varied by up to 1.3:1 dependent on the method chosen to fit the raw crack growth rate data.

5.2 Predicted fatigue endurances varied by up to 5:1 dependent on the equation chosen to describe crack growth rate data at different stress ratios.

5.3 A tabular input of crack growth rate data at individual stress ratios is recommended as the most appropriate method to describe crack growth rate data at different stress ratios.

5.4 In general, calibrated models produced reasonable predictions of the constant amplitude fatigue endurances, i.e. within a factor of 2 of the experimental data.

5.5 Experimentally measured delay lengths in SVAL tests were greater than predicted in 90% of tests.

5.6 Experimentally measured delay lengths in SVAL tests were greater than the calculated plastic zone sizes.

5.7 Crack growth predictions of Asterix and Rotorix are extremely sensitive to small changes in near threshold crack growth rates at high stress ratios.

5.8 All models, other than Kraken, generally predicted non-conservative fatigue endurances

5.9 Linear summations of crack growth rates generally resulted in non-conservative predictions.

6 RECOMMENDATIONS

This project examined a potential procedure for predicting crack growth, consisting of model calibrations for increasingly complex geometries and loading actions. Whilst it has been demonstrated that this procedure gives improved predictions, it does not always yield acceptable predictions. It is considered that the CAL optimisation is an important stage but the SVAL optimisation needs to be re-examined. The SVAL stage was highly demanding in terms of experimental effort and further work should be carried out to determine the most appropriate tests to be performed to ensure adequate model optimisation. In particular the emphasis of this work should be on the effects of underloads rather than overloads and thereby examine crack acceleration as well as crack retardation effects.

Comparison of model predictions with experimental data showed that the effects of periodic overloads were not described well by the models. In general, the cyclic interval during which crack retardation was effective could be adequately described by the models although optimisations were required to achieve this. However, the crack growth increment over which crack retardation occurred was poorly described by all of the models. Even after optimisation, all models underestimated the overload affected crack growth increment. Further work should be undertaken to examine whether the experimental procedures adopted are valid and whether parameters other than plastic zone size affect the crack growth increment during which crack retardation occurs.

Perhaps the most concerning outcome of this work was the non-conservative predictions from most models when a linear summation of crack growth rates was made for Asterix and Rotorix loading. It was shown that the predictions were particularly sensitive to crack growth rate data fits in the near threshold region at high stress ratios. However, given a wide range of data fits, all of which gave a reasonable representation of the constant amplitude data, non-conservative predictions still resulted. The only conservative predictions resulted from fits which had lower thresholds and considerably faster growth rates than the experimental constant amplitude data. A number of aspects need to be addressed in future programmes, particularly the definition of methods to describe crack growth data in near threshold regions and determination of the effect of crack length on near threshold crack growth behaviour.

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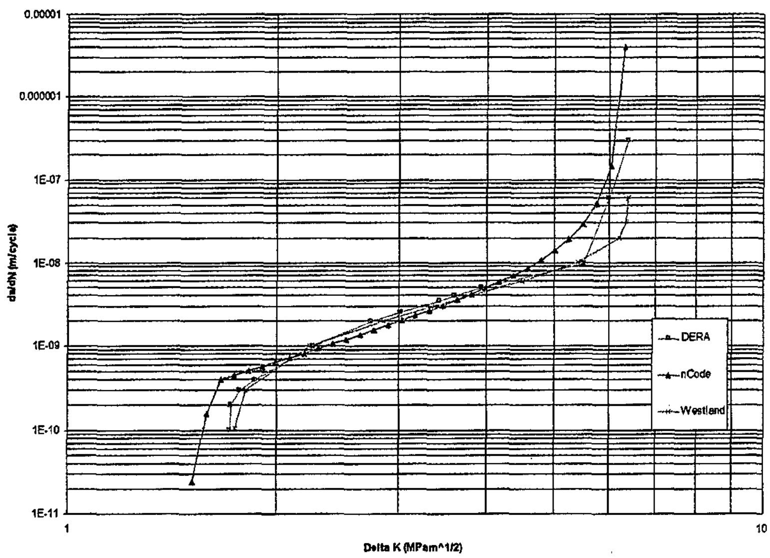

Figure 1 Fits to raw data – Titanium R = 0.9

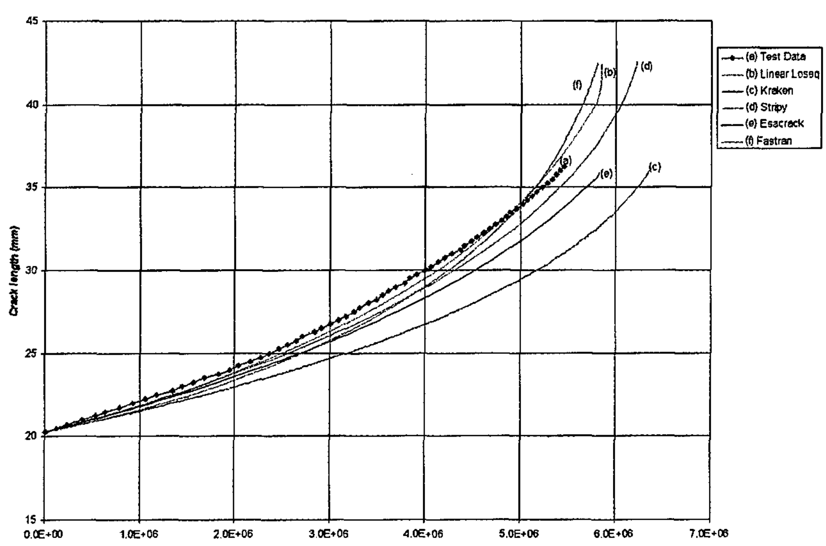

Figure 2 Predicted and experimental crack growth – CAL-Titanium R = 0.9

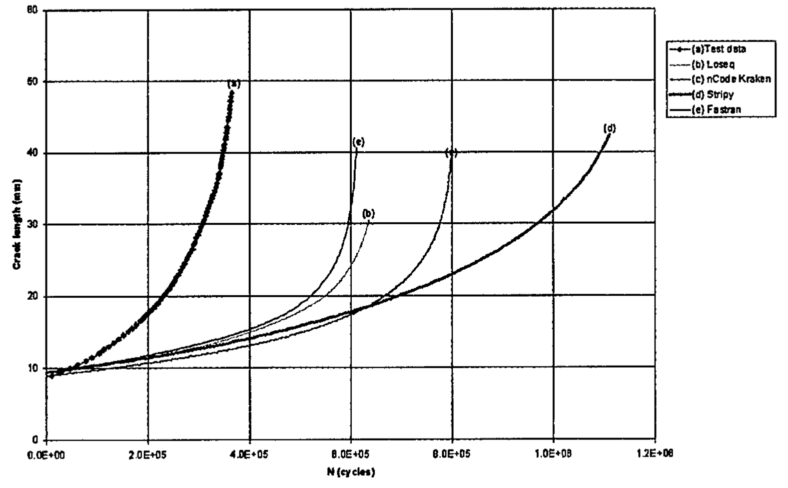

Figure 3 Predicted and experimental crack growth – CAL-Titanium R = -1.5

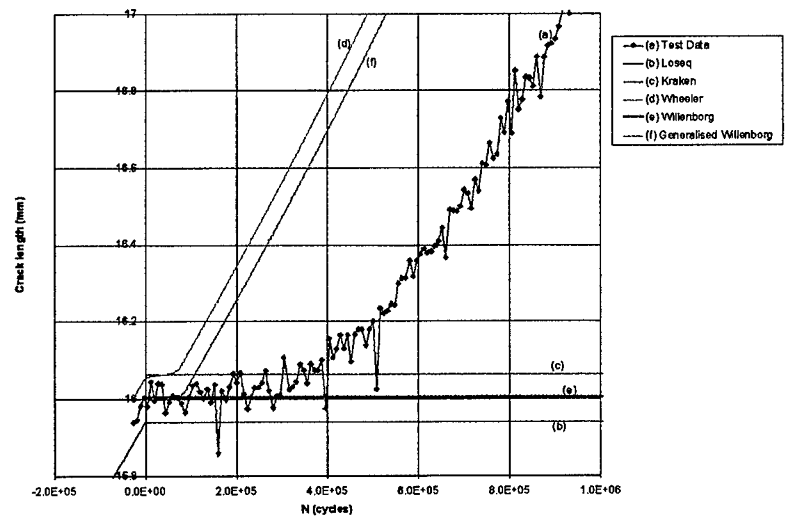

Figure 4a Effect of model optimisation – Blind SVAL Aluminium-Lithium

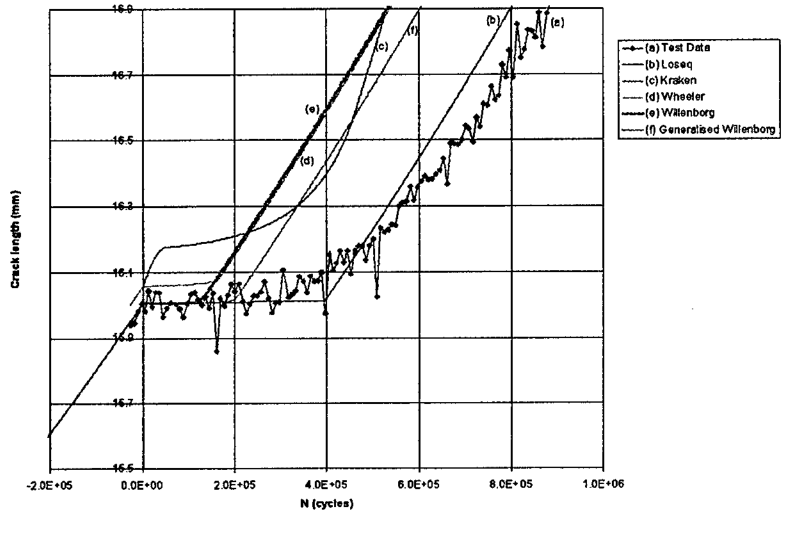

Figure 4b Effect of model optimisation – Optimised SVAL Aluminium-Lithium

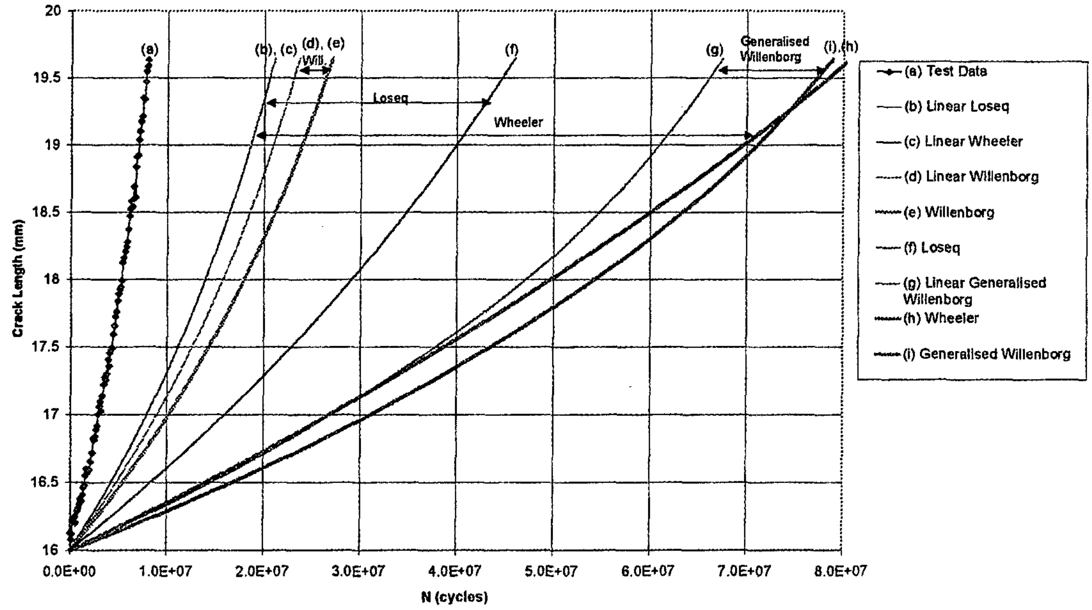

Figure 5 Load interactions predicted by the different models

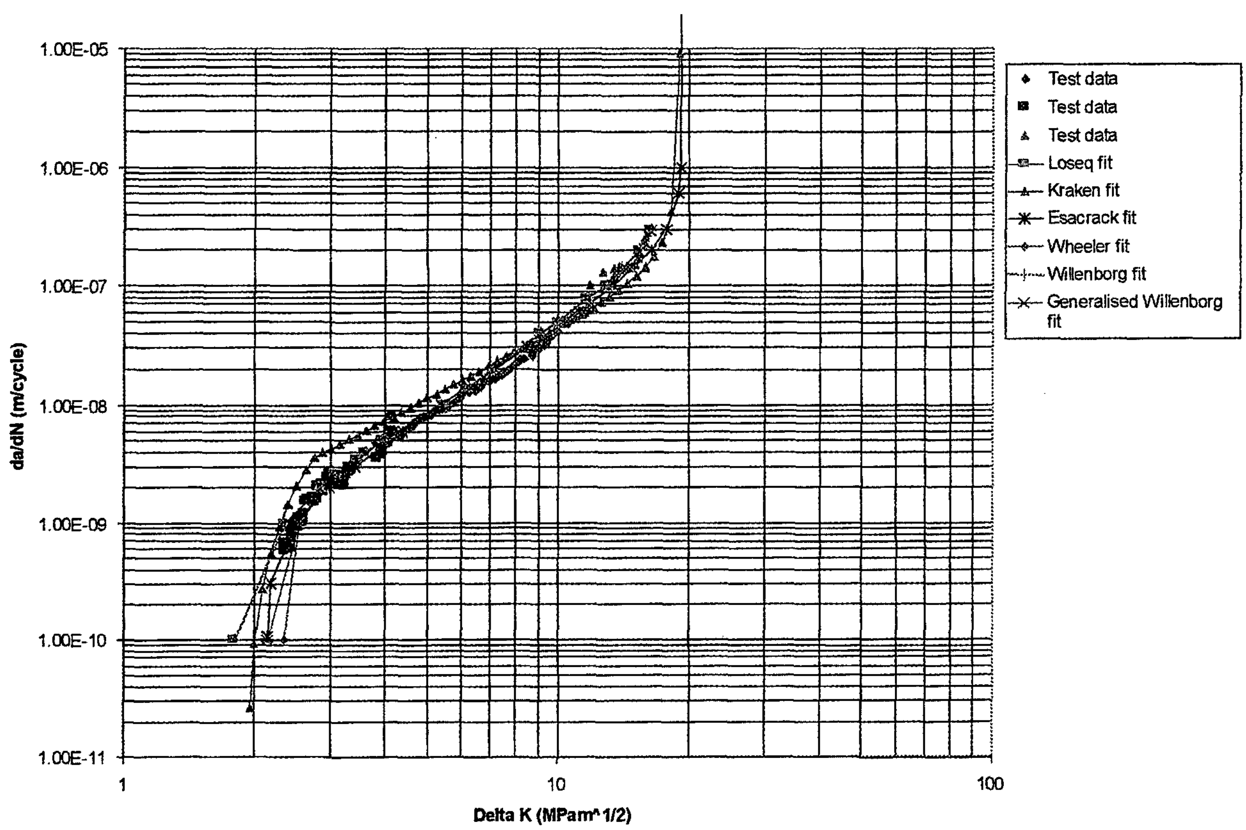

Figure 6 Crack growth data fits – Titanium R = 0.7

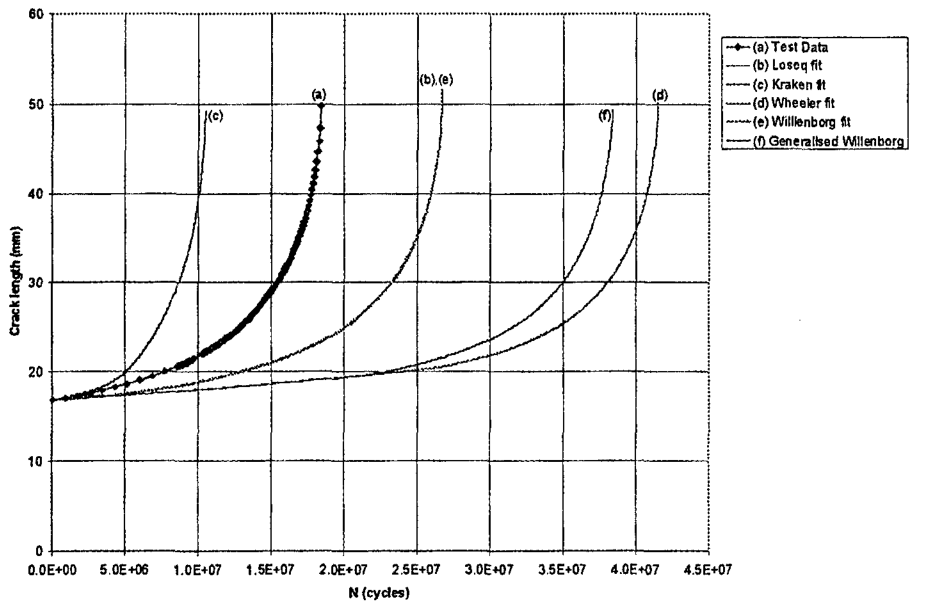

Figure 7 Effect of data fit selections on predicted crack growth for Rotorix 8

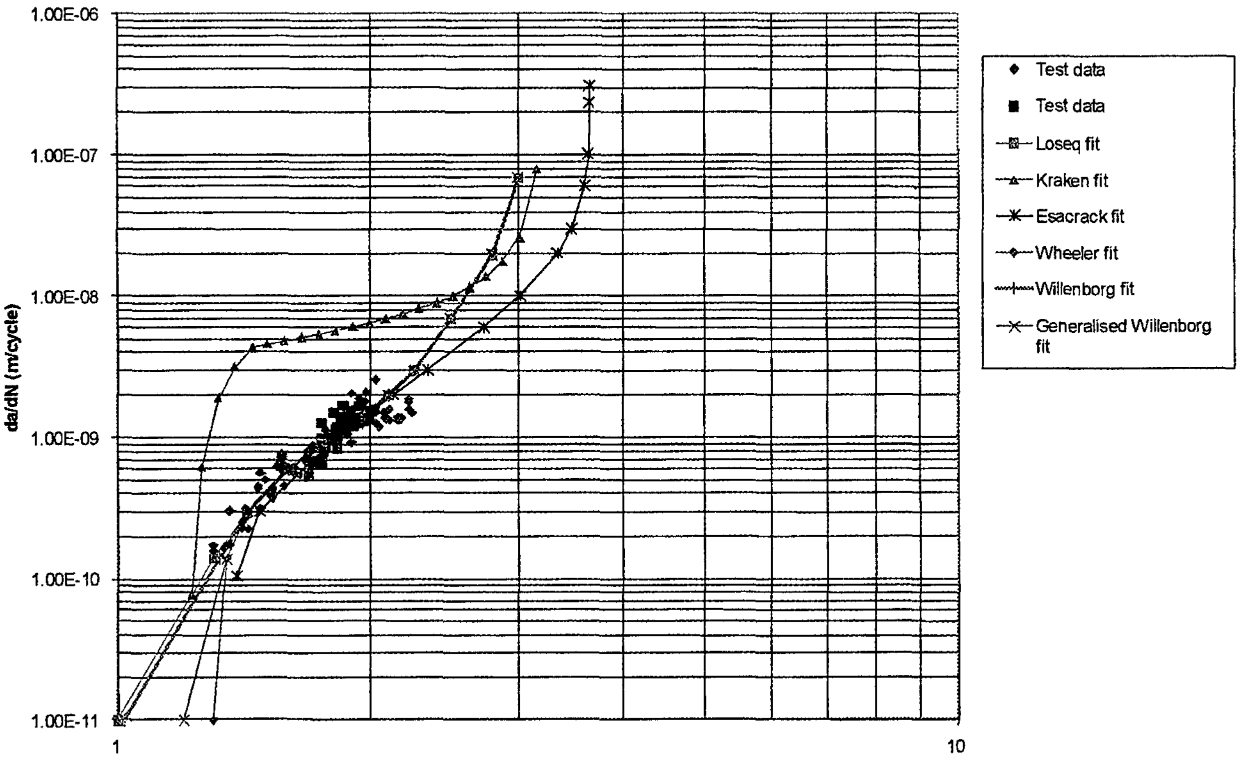

Figure 8 Crack growth data fits Aluminium-Lithium R = 0.9

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